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14. ABSTRACT
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Operational Characteristics of a Periodic Plasma Torch

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***Abstract*—Development of a plasma torch, which is intended as an ignition aide within a supersonic combustor, is studied. The high-voltage discharge and plasma plume generated by the torch module are described in a quiescent environment and in a supersonic crossflow. Voltage–current characteristics of the discharge and optical images of the plasma plume are used to characterize the operation of the torch module. The principal advantages of this torch module are its compact design, durability, and operational flexibility. The torch module can be operated in periodic or pulsed modes, depending on the power supply used. In the periodic mode presented in this paper, the capacitors are charged at the line frequency of 60 Hz resulting in a cyclical discharge at a frequency of 120 Hz. In this mode, peak and average powers reaching 8 and 2.8 kW, respectively, are demonstrated. The energy can be as high as 46 J per cycle, which is mainly limited by the power handling capability of the power supply. The penetration height and the volume of torch plume into a Mach 2.5 supersonic flow, typical for a supersonic combustor startup condition (vis-à-vis the crossflow velocity), are investigated. In addition, ignition of ethylene fuel in a Mach 2 supersonic flow with a total temperature of 590 K and pressure of 5.4 atm is demonstrated.**

***Index Terms*—Ignition aide, plasma jet, plasma torch module, supersonic combustor.**

I. Introduction

There is considerable interest in the development of plasma sources having open structures. Such plasma sources have applications in a variety of areas including, spray coating and materials synthesis [1], [2], microwave reflection/absorption [3]–[5], sterilization and chemical neutralization [6], [7], shock-wave mitigation for sonic boom and wave-drag reductions in supersonic flights [8]–[10], and ignition in supersonic combustors [11]–[13]. Different applications have different requirements on the plasma parameters, such as the density, temperature, volume, and duration. The periodic plasma torch module discussed here is intended as an ignition aide within a hydrocarbon-fueled supersonic combustor, and the operational characteristics of the torch module have been optimized to maximize plasma density, volume, and energy for a duration of a few milliseconds.

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For a typical hydrocarbon-fueled supersonic combustor startup scenario [14], [15], the fuel-air mixture will not autoignite and some ignition aide is necessary to initiate main-duct combustion. The residence time through a typical combustion region is short, $\sim$ 1 ms, and aides to reduce the ignition delay time and increase the rate of combustion of hydrocarbon fuels are essential to the operation of the combustor. Williams *et al.* [16] have carried out kinetics computations regarding the ignition of a kinetic surrogate for jet fuel. The computational results show that the ignition delay time is reduced by three orders of magnitude from 900 K to 1500 K due mainly to the large ignition activation energies, hence, steep temperature dependencies of the large hydrocarbon components of jet fuel. Moreover, detailed kinetic modeling shows a significant decrease in ignition delay in the presence of radicals and ionized species at mole fractions greater than 10^{-6}. The ignition delay time is decreased most significantly by these species at temperatures lower than 1500 K, suggesting that such processes are particularly important for the initiation of cold fuel-air mixtures. Therefore, ignition aides capable of delivering thermal energy and/or activated chemical species are desired.

A dc or low-frequency arc discharge can produce a dense plasma containing significant thermal energy as well as air dissociation products, plasma species, and UV radiation, all of which are beneficial in reducing the ignition delay time. Usually, an arc discharge has a very small volume. However, introducing a gas flow between the electrodes, such as in the operation of a plasma torch [17], [18], can greatly enlarge the discharge volume. The gas flow increases the length of the arc and impedes the establishment of a fixed anode hot spot. The increased arc length also has the effect of increasing the steady state arc voltage, which in turn, increases the plasma energy.

In this paper, the operation and performance of this torch module and the characteristics of the torch plasma are discussed. In Section II, airglow and time-resolved images of the torch plume are presented, and the cycle energy of the torch plasma and the voltage–current (V–I) characteristic of the discharge as a function of the air supply pressure (to the module) are investigated. The penetration height and the volume of the torch plume into a Mach 2.5 supersonic flow, typical for a supersonic combustor startup condition, and the ignition of ethylene fuel in a Mach 2 supersonic flow are presented in Section III.

II. Torch Plasma in a Quiescent Environment

The construction procedure and components of an earlier version of the plasma-torch module have been described in detail

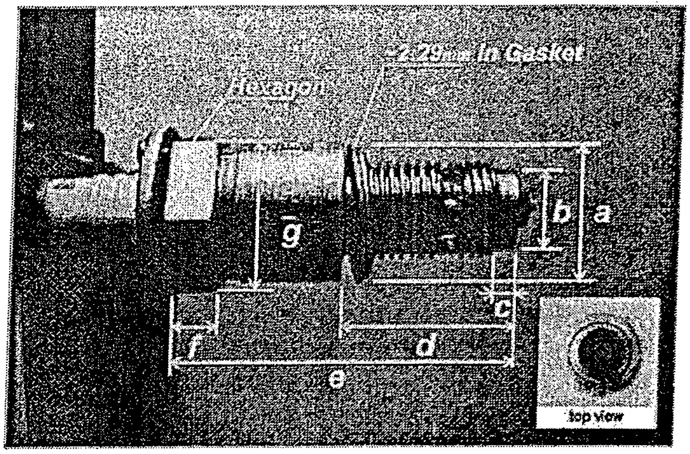

Fig. 1. Photo of the plasma torch module. The dimensions measured in millimeters (inches) are given by: $a = 19.66(0.774)$; $b = 11.81(0.465)$; $c = 2.54(0.1)$; $d = 21.34(0.84)$; $e = 42.22(1.662)$; $f = 5.44(0.214)$; and $g = 20.45(0.805)$.

in a previous publication [18] and only the recent modifications are discussed here. A photograph of the plasma torch module described in this paper is shown in Fig. 1, and some of its unique features include the following:

1) *compact size*—can be easily mounted to a base wall and requires no water-cooling;
2) *variable duty cycle*—can deliver high peak powers while maintaining low-average power consumption;
3) *high mass flow operation*—can deliver 10 s of grams of feedstock per second;
4) *durability*—can be run for long periods with an air feedstock;
5) *high-voltage operation*—rather than running at high current, the torch runs at high voltage, which reduces the power loss to the electrodes leading to longer electrode life.

The torch module is fabricated using a surface-gap spark plug (Nippon Denso, ND S-29A), which has a concentric electrode pair, as the frame. For torch operation, a gas flow between the electrodes is necessary. Thus, the original electrode insulator, which fills the space between the cathode and anode, is replaced with a new one taken from a different spark plug (Champion RN 12YC). This new ceramic insulator has a smaller outer diameter than the original one; hence, an annular gap between the electrodes is created for the gas flow. Moreover, the central electrode (anode) set in the new ceramic insulator is replaced by a solid 0.24-cm-diameter tungsten rod, which is held in place concentrically with the cathode by the new insulator and axially by a setscrew in the terminal post. The relatively high melting point of tungsten is desirable in the high-temperature environment of the arc. Eight holes of 2-mm diameter each are drilled through the frame of the module in the section having screw thread as seen in Fig. 1. The torch module is designed to screw into a plenum chamber (not shown) where feedstock gas is supplied and flows through the holes into the region between the ceramic insulator and the outer electrode. The geometry of the electrodes and the dimensions of the parts in the frame of the module are presented in Fig. 1. This torch module has a relatively large gap, 2.7 mm, between the electrodes compared to the gap used in nontransferred dc plasma torches which are usually less than 1 mm [1], [19]. The discharge is restricted to occur outside the module since the ceramic insulator is inserted between the electrodes. This geometry enables the torch to be operated at very low as well as high supply gas flow rates. On the other hand, typical nontransferred dc plasma torch modules have a limited operational flow range because sufficient gas flow to push the arc into the anode nozzle is required. Restricting the discharge to occur outside of the torch module has the additional advantage of reducing the power loss to the electrodes. The torch is operated in a periodic mode, rather than in a dc mode, because high peak powers can be obtained over a few milliseconds while maintaining lower average power consumption. Periodic mode operation also allows for more cooling of the electrodes by the feedstock gas between discharges. Both effects greatly extend the electrode lifetime.

The power supply used in this study is described in the following. A power transformer with a turn ratio of 1:25 is used to step up the input voltage of 150 V [root mean square (rms)] to 3.75 kV (rms). The input voltage is provided by the single phase 208 V (rms) power line, which is reduced to 150 V (rms) by a Variac. Twelve 1-μF, 2.3-kVAC capacitors are connected to obtain an equivalent 3-μF, 4.6-kVAC rating. This capacitor assembly is connected in series with the transformer and the electrodes. A serially connected diode assembly consisting of four parallel-connected 15-kV, 750-mA rated diodes (to increase the current rating to 3 A) and four parallel-connected resistors ($R =$ 16 kΩ each) is placed in parallel to the electrodes to further step up the peak voltage. The series resistor is used to protect the diode by preventing the charging current of the capacitor assembly from exceeding the specification (750 mA) of each diode and to regulate the time constant of the discharge. A resistance of 4 kΩ optimizes the power factor of the power line. Since the resulting resistance times capacitance (RC) time constant of 12 ms is longer than the half period of the 60-Hz line input (8.5 ms), the discharge in the torch module occurs in both half cycles (120 Hz operation) regardless of whether the diode is forward or reversed biased. If the capacitance is reduced to 1 μF, reducing the RC time constant to 4 ms, the discharge occurs only during the half cycle when the diode is reversed biased. In the other half cycle, when the diode is forward biased, the capacitor is charging, which quickly reduces the available voltage for the discharge.

The torch is operated in the open air using compressed air as the feedstock unless otherwise noted. The shape of the torch plasma varies with the gas flow rate which is proportional to the supply pressure of the plenum chamber discussed earlier. Starting with a relatively low supply pressure of 1.7 atm (all pressures given are absolute rather than gage values), the torch plasma as shown in Fig. 2(a) has a divergent shape. It becomes less divergent as shown in Fig. 2(b) when the supply pressure is increased to 2.4 atm. When the supply pressure applied to the plenum chamber exceeds 3.4 atm, the flow speed at the exit of the torch module becomes supersonic as evidenced by the appearance of shock structure at the exit of the torch nozzle in schlieren images of the flow field. Fig. 3 shows an example of a schlieren image of the flow exiting the torch module with a supply pressure slightly greater than 3.4 atm. The shock discs

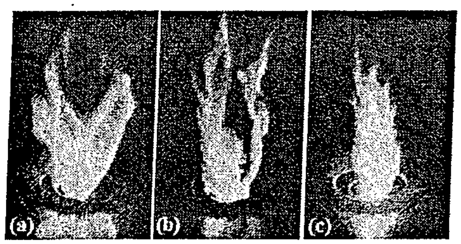

Fig. 2. Torch plasmas produced by the torch module with supply pressures of (a) 1.7, (b) 2.4, and (c) 6.4 atm. The images were taken at 28.33° off the side view line. Equivalent horizontal and vertical dimensions are calculated to be 24 × 44 mm.

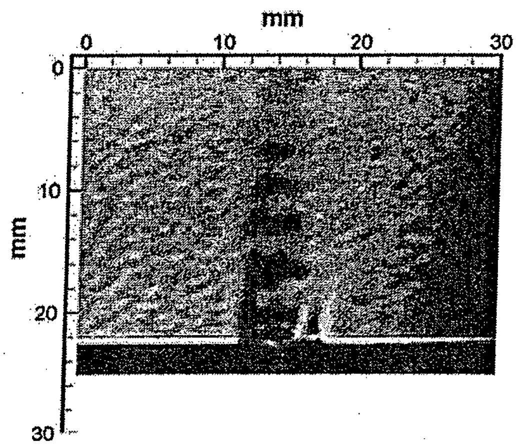

Fig. 3. Schlieren image of the flow out of the torch module with a supply pressure slightly larger than 3.4 atm.

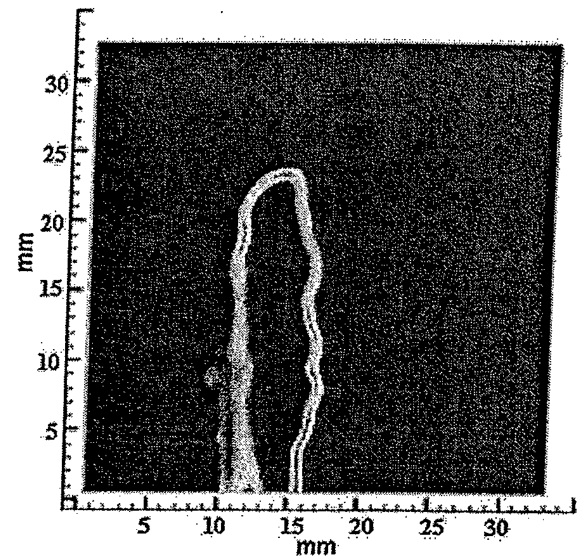

Fig. 4. False-color image of an arc loop in torch plasma taken by an intensified CCD camera with an 80-ns exposure though a 239-nm interference filter, 10-nm FWHM. The diffuse emission surrounding the arc loop is from NO laser-induced fluorescence (see text).

are clearly visible in the image. When the flow speed exiting the torch module becomes supersonic, the torch plasma plume becomes more collimated as illustrated in Fig. 2(c), where the supply pressure was set to 6.4 atm. The torch plasma plume maintains a high degree of collimation as the supply pressure is increased from 3.4 atm to the highest available laboratory level of 7.6 atm.

As a consequence of the high-voltage nature of the discharge, the arc loop can be many times the distance between the anode and cathode. The arc loop structure is illustrated in the image (typical of those recorded) shown in Fig. 4, which was recorded through a 239-nm interference filter, 10-nm full-width at half-maximum (FWHM), with an intensified charge coupled device (CCD) camera (Roper Scientific PIMAX) set for an 80-ns exposure time. The current loop is coincident with the thin, intense emission loop shown in the figure. For this measurement, pure nitrogen with a pressure of 1.7 atm was supplied to the torch module. The horizontal extent of the arc loop is ca. 3.2 mm, whereas the vertical extent is about 2.5 cm. Such an extended arc loop increases the path length of the charged particles in the discharge by more than 15 times the direct path length from the cathode to the anode. Also shown in Fig. 4 is laser-induced fluorescence (LIF) from nitric oxide (NO) obtained using a Nd:YAG-pumped dye laser system to generate laser radiation at 226 nm probing the overlapped $Q_1(12.5)$ and $Q_2(19.5)$ transitions in the $\delta(0,0)$ band of NO. The LIF image appears as the diffuse, less intense background and is best seen on the left side of the figure toward the outer portion of the arc loop. NO is produced within the torch plume in the region where the hot torch gas (pure N_2), i.e., the gas near the arc, mixes with quiescent laboratory air. Thus, NO is formed primarily near the outer portion of the arc loop.

The extended arc loop structure produced with this torch module has several distinct advantages. For instance, such images indicate that high temperature, dissociated, and ionized air extends well above the surface of the torch module which is important for ignition applications. The long electrode lifetime may in part be due to extended arc length since the charged particles' kinetic energy is reduced before hitting electrodes. Furthermore, the conversion of electrical energy to plasma energy may be enhanced due to the longer interaction region. Images such as that shown in Fig. 4 indicate that the length of the arc loop is not strongly sensitive to the flow rate, but the width of the loop becomes narrower as the flow rate increases which is consistent with the change in the flowfield structure as the jet becomes underexpanded and supersonic with increased supply pressure.

The time varying V–I of the discharge were measured using a digital oscilloscope (Tektronix TDS3012 DPO 100 MHz and 1.25 GS/s) for each supply pressure p_0 in the range from 1.2 to 7.6 atm. Presented in Fig. 5(a) is a V–I characteristic plot from the results obtained with a supply pressure of 6.67 atm. The V–I characteristic plots shown in Fig. 5(a) indicate that the discharge is in the arc mode in both half cycles. In addition, significant hysteresis is observed in the half cycle when the central electrode is positive. The asymmetry of the V–I curve is due to the physical difference between the electrodes. The discharge normally initiates in the region near the central electrode where the applied electric field concentrates due to the cylindrical geometry. When the central electrode is positive, it collects electrons produced by the discharge. The transit-time loss of electrons increases the breakdown voltage considerably. After the discharge initiates, it evolves quickly to the high-current low-voltage arc mode. In this regime, the breakdown voltage drops dramatically to a value determined by recombination/attachment losses rather

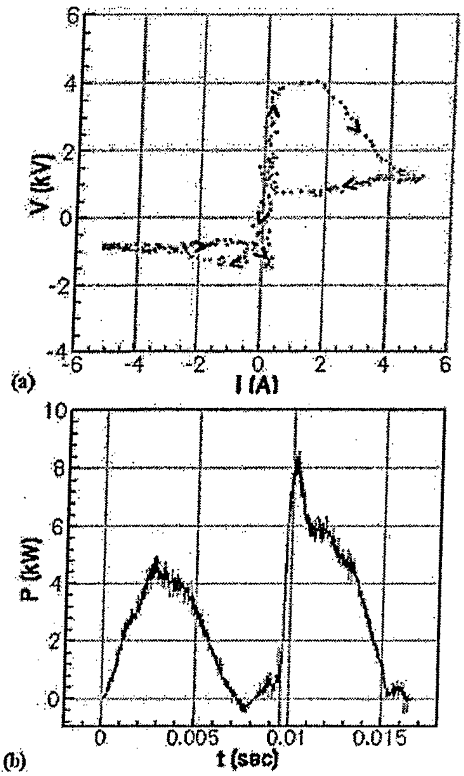

Fig. 5. (a) *V–I* characteristic of the discharge in one cycle. (b) Instantaneous power function $P = VI$ obtained with a supply pressure of 6.67 atm.

than inthe transit-time losses. It is the transition of the breakdown voltage during the discharge from transit-time losses to recombination/attachment losses that bifurcates the *V–I* relation to form the hysteresis loop shown on the right hand side of Fig. 5(a). In the reverse cycle, the ring electrode collects electrons resulting in insignificant transit-time losses. In this case, the breakdown voltage is mainly determined by the recombination/attachment losses in the entire discharge period.

The product of the *V–I* functions gives the instantaneous power function. The result in one cycle is presented in Fig. 5(b). As shown, the cycle having the larger peak power of about 8 kW is the power function of the discharge lasting about 5 ms with the diode in the circuit forward biased. In the reverse bias phase, the discharge lasts longer at about 6 ms, but the peak power is reduced to 5 kW. The average power of the torch over one cycle exceeds 2.7 kW. It is noted that the added diode in the circuit serves to reduce the voltage requirement of the transformer output to produce a reliable discharge. Integrating the power function over one cycle determines the cycle energy of the torch, i.e., the thermal energy carried by torch plasma in each cycle. The results show that this cycle energy varies with the pressure p_0 as shown in Fig. 6. In the regime of subsonic flow, the cycle energy increases to the maximum of about 28 J at $p_0 = 2.4$ atm. The cycle energy increases again in the supersonic flow regime and reaches a maximum of about 46 J at $p_0 = 6.4$ atm. The transition of the flow speed from subsonic to supersonic corresponds to the dip at $p_0 = 3$ atm in the plot. Generally, the cycle energy of the torch increases with the increasing flow rate, i.e., the supply pressure p_0 of the module, before reaching the peak value in the region between 5.4 – 6.4 atm. The increase of the cycle energy with supply pressure below 6.4 atm is realized because the supplied gas flow works to increase the transit time of charged particles by keeping the discharge away from the shortest (direct) path between two electrodes. An increase of the current path also increases the effective resistance in the discharge and, hence, the discharge voltage increases, as observed in the forward bias phase. Consequently, the plasma energy increases. However, when the flow rate becomes too high (i.e., $p_0 > 6$ atm), the mobility of charged particles may become affected by the flow leading to a reduction of the discharge current. The decreased discharge current results in a decrease of the torch energy. This effect may be responsible for the decrease of the cycle energy with increasing pressure for $p_0 > 6$ atm shown in Fig. 6.

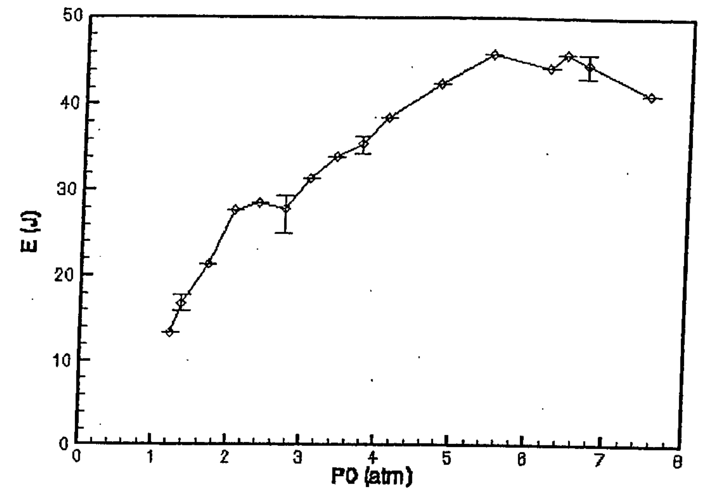

Fig. 6. Dependence of the cycle energy E of the torch plasma on the supply pressure.

III. Torch Behavior in a Mach 2.5 Crossflow

Experiments measuring the penetration depth of the torch plasma into a supersonic crossflow are conducted in a test section of a supersonic blow-down wind tunnel having a cross section of 38×38 cm. The upstream flow has a flow speed 570 m/s, a static temperature of 135 K, and a pressure of 1.8×10^4 N/m^2 (ca. 0.20 atm). A wind-tunnel stand is used to support the torch module in the test section. The torch plume is injected normally into the supersonic flow, and the performance of torch plasma in terms of its height and shape in the supersonic flow is observed.

A shadowgraph of the bow shock wave generated in front of a torch module supplied with 4.1 atm of air in a Mach 2.5 crossflow (from left to right) shown in Fig. 7(a). The generation of the bow shock is expected for a jet injected normally in a supersonic crossflow because the jet acts an obstruction to the oncoming flow. The sharper shock front, also appearing in the middle of the stand image but the having smaller shock angle, is generated by the edge of the torch module that is not exactly flush with the stand surface. The two oblique shock waves on the left-hand side of the image are generated by the left-side edge of the wind tunnel stand, which is slightly misaligned with the flow.

An airglow image of the torch plume in a Mach 2.5 crossflow (from left to right) with 4.1 atm of air pressure supplied to the

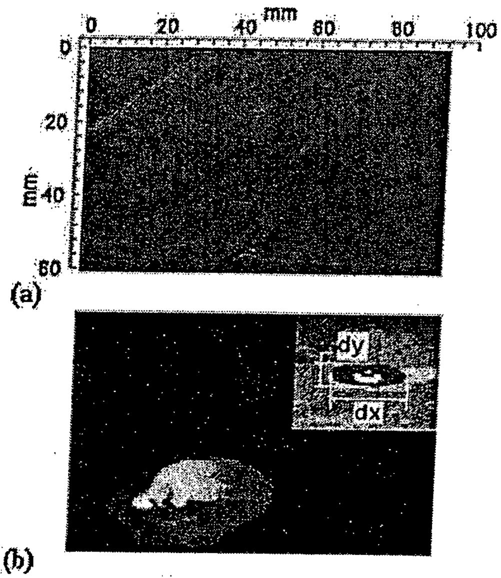

Fig. 7. (a) Shadowgraph of the torch jet in the Mach 2.5 crossflow (from left to right). An oblique shock wave is generated in front of the torch as a result of the jet. (b) Airglow image of ac torch plasma in the Mach 2.5 crossflow (from left to right). In the insert of (a), $d_x = d_y = 11.4$ mm define the horizontal and vertical scales of the photo.

gas chamber of the torch module is shown in Fig. 7(b). As can be seen in the figure, the supersonic flow causes significant deformation of the shape of the plasma torch plume. The height of the torch is reduced significantly as the plume is swept downstream by the high-speed flow. Nevertheless, the torch plume penetrates into the supersonic crossflow by more than 1 cm and extends a centimeter downstream. Increasing the supply pressure leads to greater penetration of the plasma plume into the crossflow.

Initial evaluation of plasma-assisted ignition is conducted in a supersonic, Mach 2 flow facility with heated air at a total temperature and pressure of 590 K and 5.4 atm, respectively. The resulting static temperature was thus $\sim$ 330 K, still a relatively low value insofar as ignition is concerned. This facility allows testing of an individual concept with both gaseous and liquid hydrocarbon fuels without a cavity based flame-holder. In the tested configuration, a 15.2×30.5 cm test section floor plate fits into a simulated scramjet combustor duct with an initial duct height of 5.1 cm. At the upstream edge of the test section insert, the simulated combustor section diverges on the injector side by 2.5°. This particular hardware was intentionally designed not to study main-duct combustion (ignition of the entire duct), but to reduce the chance of causing main-duct combustion by limiting the equivalence ratio of the tunnel below 0.1. In particular, this was accomplished by placing the fuel injector at the centerline of the tunnel and not adding any flame-holding mechanisms such as a cavity or backward-facing step. This approach allows the interactions of the fuel plume with the plasma torch to be studied by itself, and any flame produced is strictly created by this interaction, hence, decoupling the ignition and flame-holding problems as much as possible from the combustor geometry. Tests have been conducted using gaseous ethylene fuel, with the 15° downstream-angled single hole.

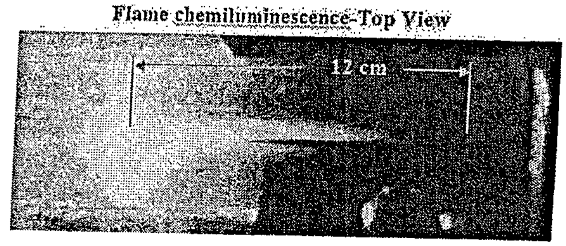

Fig. 8. Single frame of flame chemiluminescence viewed from the top taken from video recordings of the 120-Hz plasma torch in operation 5 cm downstream of the ethylene-fueled single-hole injector. Fuel (5.3 gm/s, 318 K), Freestream (5.4 atm, 586 K), Torch (5-KW Peak, 470 SLPM Air).

The 120-Hz plasma torch module was evaluated and was found to produce a substantial flame plume as observed both from flame chemiluminescence and OH planar laser induced fluorescence (discussed in a future publication). The flame chemiluminescence (blue emission in the tail of the plume) is illustrated in Fig. 8, which shows a single frame taken from video recordings of the 120-Hz plasma torch in operation 5 cm downstream of the ethylene-fueled single-hole injector. Several feedstock flowrates were tried over the torch module operational range and a flowrate of $\sim$ 500 SLPM was determined to produce the largest visible flame for the current electrode configuration. Air produced a larger flame when compared to nitrogen as the torch feedstock. This difference in flame size indicates that this type of flame is very sensitive to the local equivalence ratio and coupling of the ignition source with the mixture.

IV. Conclusion

Plasma-based ignition offers a technology alternative for adding large amounts of energy to specific regions of the supersonic flow-field. Duration and repetition of the applied power can be tailored to the ignition requirements. Power supplies can be developed to deliver enormous amounts of energy for short periods of time. Average power requirements, pulse duration and frequency, and spatial location are all within the designer's control. At issue is whether control over these parameters is sufficient to accelerate the fuel-air kinetic rates enough to achieve the self-sustaining condition within the supersonic flow-path.

The periodic plasma torch module discussed here is intended as an ignition aide within a hydrocarbon-fueled supersonic combustor, and the operational characteristics of the torch module have been optimized to maximize plasma density, volume, and energy for a duration of a few milliseconds. The operational characteristics of the plasma torch module operated at 120 Hz were discussed. The torch design is based on standard components but is modified for inclusion of a gas feedstock supply. The principal advantages of this torch module are its compact design, durability, and operational flexibility. The relatively large gap between electrodes results in a high-voltage discharge, and the ceramic insulator inserted between the electrodes forces this discharge to take place outside the module. As a consequence of these design features, this torch module produces a plasma with an extended structure which enhances the conversion of electrical energy to plasma energy due to the elongated interaction region. These features are different from discharges produced in conventional nontransferred dc plasma torches. The peak and average powers reaching 8 and 2.8 kW, respectively, were demonstrated, and maximum cycle energy of 46 J was observed. Furthermore, good penetration of the plasma torch plume into a Mach 2.5 crossflow was demonstrated. The 120-Hz plasma torch module was evaluated and was found to produce a substantial flame plume 5 cm downstream of an ethylene-fueled single-hole injector in supersonic, Mach 2 flow facility. These aspects are important for supersonic combustion applications where energy deposition, penetration, and ignition are critical issues.

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